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Correlative Dynamics Studies Using the Air Force Sodium Lidar and Associated Instrumentation at the ALOMAR Observatory

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Dr. Dave Fritts

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NWRA-CoRA-03-R266

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Air Force Office of Scientific Research
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Arlington, VA 22203-1954

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13. SUPPLEMENTARY NOTES

14. ABSTRACT
The present award was for correlative use of the Weber lidar (built and installed at ALOMAR under previous DURIP funding) for dynamics studies in the mesosphere, thermosphere, and ionosphere. Initial activities focused on expanded capabilities, frequency stability, and stable operations of the Weber lidar. Initial measurements demonstrated a dual-beam capability, off-vertical measurements of momentum fluxes, and full daytime operations. Efforts during 2002 and 2003 emphasized collaborative measurements in support of the MaCWAVE summer and winter rocket and ground-based measurement campaigns. Analyses of these results have revealed a highly active and variable summer mesopause environment, with large wave amplitudes, extreme temperature and wind gradients, and strong turbulence and mixing both above and below the mesopause. Winter data reveal a similarly active environment exhibiting strong tidal motions, filtering of the gravity wave spectrum by mean winds, and strong temporal variability of the motion fields. Subsequent data analyses will quantify these dynamics further. Related theoretical efforts contributed to assessments of the consequences of local body forcing by spatially and temporally localized gravity wave breaking and to an understanding of the effects of gravity wave breaking and turbulence generation on wave amplitude and the character and statistics of turbulence that results.

15. SUBJECT TERMS

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FINAL TASK REPORT

Instructions: Provide all information identified below for the last FY only. List Research Objectives in bullet format. Provide Summary of Progress and Forecast for next FY in narrative format.

Research Title: Correlative Dynamics Studies Using the Air Force Sodium Lidar and Associated Instrumentation at the ALOMAR Observatory

Principal Investigator: David C. Fritts
Co-Principal Investigator: C.-Y. "Joe" She

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AFOSR Program Manager: Major Paul Bellaire

Research Objectives:

1. Definition of gravity wave propagation throughout the lower and middle atmosphere in order to quantify the relative roles of sources and filtering by mean and low-frequency winds in defining the wave field and anisotropy in the mesosphere, thermosphere, and ionosphere (MTI);

2. Definition of spectral evolution of gravity waves with altitude in order to assess, together with parallel modeling activities, the physical processes accounting for wave dissipation and spectral shape;

3. Identification of the interactions among gravity waves and tidal motions that account for gravity wave damping and the evolving anisotropy of the gravity wave spectrum at MTI altitudes;

4. Identification of the effects of the polar vortex on gravity wave propagation, fluxes, and dynamics;

5. Definition of gravity wave and tidal forcing of the MTI mean circulation and thermal structure in the presence of variable motion fields and wave-wave interactions, since the mean forcing may be a small residual when wave interactions, anisotropy, and momentum and heat fluxes are large;

6. Inference of the transports of constituents at polar latitudes and interactions between dynamics and chemistry; and

7. Quantification of the statistical forcing and variability imposed on the thermosphere at greater altitudes by the strong wave forcing and interactions occurring in the MTI.

Fiscal Year 2003 Funding Summary ($K):

In House	Capital Equip. (> $5,000 each)	Subcontractor	Total
$81,471		$54,032	$135,503

Summary of Progress:

Prior to this award, the Air Force funded, under the Defense University Research Instrumentation Program (DURIP), the development and installation of a state-of-the-art sodium resonance lidar (the Weber lidar) for studies of the dynamical influences on the mesosphere, thermosphere, and ionosphere (MTI). This lidar has now been operational at the ALOMAR (Arctic Lidar Observatory for Middle Atmosphere Research) facility in northern Norway for three years.

Activities during 2001 led to significant further improvements in the Weber lidar operation, including beam alignment for off-vertical two-beam operations, greater frequency stability, and greater output power. In March 2001, Biff Williams of CSU and Dorothy Gibson-Wilde of NorthWest Research Associates, Inc., Colorado Research Associates division (CoRA) operated the Weber lidar extensively and made the first off-vertical measurements, obtaining temperature and zonal wind measurements for the first time. During summer 2001, considerable improvements in the sum-frequency generator (SFG) were made by 1) installing an electronic scheme to lock the SFG to the D2a frequency, 2) replacing the initial $LiNbO_3$ crystal with one having enhanced performance, and 3) implementing an automated procedure for tuning and power-up of the SFG.

Efforts during 2002 had two components, further improvements in the stability and operation of the Weber lidar and winter and summer measurements addressing wave dynamics and atmospheric structure. As a result, the Weber lidar now achieves high-power, dual-beam daytime and nighttime operations employing beams in any of the cardinal directions with photon counts that are close to the theoretical limit. Further efforts during 2003 have included additional measurements and system work at ALOMAR and have in particular focused on analyses of correlative data collected during the summer rocket and ground-based measurement campaign. Earlier reports documented initial measurements

and validation of wind and temperature estimates with other instrumentation. Our discussion here will focus instead on scientific applications of the lidar and the analyses that have been performed with the system to date.

A comparison of winds was made previously with the ALOMAR meteor and MF radars to assist in the validation of the wind measurements. The comparison between Weber lidar and meteor radar winds was excellent, but the comparison between these two data sets and the MF radar winds exhibited some biases. Upon review of the data, it was determined that there was a range problem with the MF radar. After correction of the range problem, the MF winds were in much better agreement with the other data sets. We have noted in the more recent measurements, however, that in the presence of strong vertical gradients of wind, the meteor radar tends to badly underestimate wind shears. This has been traced by Australian colleagues to a vertical smearing of wind estimates by the meteor radar when significant fractions of the meteors occur at very low elevation angles. This also confirms the value of Weber lidar winds at high altitudes as the only routine means of defining large wind gradients. Clearly, only the Weber lidar or very expensive and infrequent in situ rocket measurements can capture large gradients and small-scale features in the temperature field. And only the Weber lidar offers this possibility for winds. Momentum flux measurements require higher time resolution and two coplanar off-vertical telescope beams, but are accurate at coarser vertical resolution because momentum fluxes are dominated by waves having large vertical scales. Momentum fluxes were estimated during our first coplanar beam experiment in January 2001 from five hours of data and were displayed in our last annual report. While preliminary due to the limited duration of the data set, the momentum flux profile exhibited a general anticorrelation with the mean winds which is in reasonable agreement with such measurements employing radar techniques at the former Poker Flat VHF radar in Alaska at a comparable latitude. Further momentum flux estimates are now able to be validated with the new SAURA MF radar recently installed at ALOMAR by our German colleagues.

As noted previously, measurements in collaboration with the MaCWAVE/MIDAS rocket program and overpasses of the TIMED satellite during July 2002 employed coplanar E and W beams at 20 degree zenith angles to provide sensitivity to temperatures, zonal winds, and momentum fluxes accompanying the rocket salvos. Further measurements were performed in collaboration with the winter MaCWAVE rocket series launched at ESRANGE, Sweden, and lead to a spectacular merged data set that will be discussed further below. Together, these measurements in support of comprehensive field measurements represent the most extensive use of the Weber lidar to date and are good examples of the initial motivation for installation of the lidar at the ALOMAR facility. These collaborative studies have likewise enabled us to make significant progress on all of the research objectives listed above during the course of our research. Analysis of Weber lidar data in support of the MaCWAVE summer measurement program is revealing a highly dynamic mesopause environment, with significantly more gravity wave activity than thought previously to exist under summer mesopause conditions. We will be arguing as a part of the papers in the upcoming special section of Geophysical Research Letters for MaCWAVE summer program (recently approved by GRL) that part of this activity represents an enhancement over and a departure from normal gravity wave conditions at the mesopause. But other evidence of strong wave forcing is consistent with previous measurements and simply suggests that our previous views of summer mesopause dynamics were insensitive to large gravity wave amplitudes and gradients that are present under normal conditions.

Profiles of sodium density, radar signal-to-noise ratio (SNR), and Rayleigh lidar backscatter ratio (BR) are shown together for the first MaCWAVE rocket salvo in Figure 1. These data suggest that large ice particles (responsible for visible NLC) and free sodium atoms cannot co-exist, that large sodium densities occur only distinct from any enhancement in radar backscatter (SNR), and that altitudes with significant sodium densities are highly confined under summer mesopause conditions having strong upwelling below the mesopause and microphysical processes that limit free sodium densities.

Hourly-averaged temperature profiles obtained with the Weber lidar in the east and west beams are shown together with falling sphere temperatures at lower altitudes in Figure 2. These profiles reveal a dynamically very active summer mesopause environment, with significant

temporal variability, differences between the two beams (spaced at ~ 60 km) due to small horizontal wavelengths of the more significant motions, and the presence of very large temperature gradients immediately above the mesopause. Similar profiles for which we have performed a 0.5 km smoothing in the vertical are shown for each lidar beam together with an in situ CONE profile in Figure 3. Again, there are significant differences in the profiles obtained in the two lidar beams and with the CONE instrument, but we believe these to be due to the spatial separation between the measurement locations (see figure caption). Similarly large gradients in zonal winds observed during the summer MaCWAVE campaign are shown in Figure 4 for reference and reveal wind shears as large as ~ 100 m/s/km on occasion, averaged between beams and over an hour. These extreme gradients in temperature and zonal wind appear to be concentrated in the region of very high stratification immediately above the mesopause, which is itself a consequence of the strong gravity wave forcing of this region during our summer measurements. What is of greatest interest here (and in the GRL papers being prepared) is the presence of extremely large gradients of winds and temperatures and the wave instability, mixing and transport, and wave-mean flow interactions that they imply.

Correlative studies have likewise provided evidence of gravity wave filtering due to the mean wind profile present under arctic summer conditions, due to the polar vortex wind structure accompanying a stratospheric warming under winter conditions, indications of strong mixing and transport due to enhanced wave breaking in the lower thermosphere, and quantification of gravity wave variability as a driver for inter-annual variations in the arctic summer mesopause circulation and thermal structure. Though not yet complete, our winter MaCWAVE measurements also provide a potential to assess tidal filtering of the gravity wave spectrum and the mean-flow interactions that result. This superposed tidal and gravity wave field is illustrated with temperature and zonal wind cross sections for a portion of the winter MaCWAVE salvo obtained with the Weber lidar in Figure 5. Related theoretical efforts contributed to assessments of the consequences of local body forcing by spatially and temporally localized gravity wave breaking and to an understanding of the effects of gravity wave breaking and turbulence generation on wave amplitude and the character and statistics of turbulence that results. Local gravity wave breaking leads to body forces that impose significant additional gravity wave activity, and at scales that ensure that such secondary waves will penetrate preferentially to much higher altitudes. This implies a source of gravity waves not previously identified that may have implications as high as 150 km and above in the thermosphere. A related study demonstrated how similar forcing of gravity waves by deep convection could result in their penetration well into the thermosphere, to altitudes of ~ 200 km and above, and provide a potential seeding mechanism for equatorial spread-F and plasma bubbles penetrating to high altitudes. Wave breaking was described in a very high resolution numerical model and was found to have some surprising effects. The first was a much larger than expected reduction in the primary wave amplitude, by a factor of ~ 3, rather than the ~ 10% expected from linear theory (for an initial wave amplitude a = u'/(c-u_bar) = 1.1). The second effect was a strong localization of turbulence within the most unstable phase of the wave motion, with implications for mixing that remain to be fully quantified. A brief summary of efforts that have addressed our specific research goals is provided below:

1. Definition of gravity wave propagation and the role of filtering in determining the MLT wave spectrum has been addressed with 1) analyses of MaCWAVE summer campaign data quantifying gravity wave frequencies and propagation directions, 2) analysis of the responses to strong wave amplification in the lower thermosphere accompanying sharp increases in atmospheric stability, and 3) modeling of the influences of mean shears on the spectrum of wave penetrating from tropospheric and MLT sources well into the thermosphere.

2. Definition of spectral evolution of gravity waves accompanying wave instability has been addressed with both direct numerical simulations of wave instability dynamics and body force models accounting for the gravity wave generation and radiation from localized (parameterized) wave dissipation.

3. Identification of the interactions among gravity waves and tidal motions relies on suitable observational data and is being pursued with the correlative lidar, radar, and rocket data collected during the MaCWAVE winter campaign in early 2003 which exhibited large semi-diurnal tidal motions.

4. Identification of the effects of the polar vortex on gravity wave propagation, fluxes, and dynamics is likewise being performed using winter MaCWAVE data obtained under conditions of a stratospheric warming that resulted in reversal of the zonal mean flow over Scandinavia and cessation of vertical propagation of a portion of the gravity wave spectrum during our field program.

5. Definition of gravity wave and tidal forcing of the MTI mean circulation and thermal structure is being addressed both with 1) long-term measurements of momentum fluxes with the Weber lidar, where possible, and other correlative instrumentation (especially the SAURA MF radar also at ALOMAR), 2) measurements of the wave-induced mean meridional circulation with various ALOMAR instruments, and 3) analysis of tidal momentum fluxes computed from the GSWM tidal wind fields in the presence of parameterized tidal dissipation (the last of these is in a very preliminary phase).

6. Inferences of the transports of constituents at polar latitudes and interactions between dynamics and chemistry have been and are being addressed with 1) studies of the coincidence of sodium densities, PMSE, NLC, and gravity wave and turbulence dynamics and 2) correlations between strong gravity wave amplitudes, shears, and turbulence and regions of enhanced or reduced mean stratification in the MLT.

7. Quantification of the statistical forcing and variability imposed in the thermosphere at greater altitudes is being addressed both observationally and theoretically. Observational efforts are quantifying wave energies and momentum fluxes and their responses to variable mean flows. Theoretical efforts have addressed, and are addressing, responses to specific discrete wave sources and the contributions to such forcing by the various tidal components.

Appendix A: In-house Activities

Instructions: Provide all information identified below for the last FY only. "Personnel" should include each scientist or engineer who contributed to the research during the year. Publication of articles derived from the research should be listed chronologically in bibliography format. Attach reprints. List only invention disclosures derived from this specific research effort. Honors may include recognition both inside and outside the academic and Air Force science & technology (S&T) communities. Extended scientific visits may include collaboration with other research programs, both foreign and US.

Personnel:

	Name	Degree	Discipline	Involvement
In House Employees	Dave Fritts	Ph.D.	Physics	1 mo/yr
	Dorothy Gibson-Wilde	Ph.D.	Physics	2 mo/yr
	Biff Williams	Ph.D.	Physics	2 mo/yr

Subcontract Personnel:

C.-Y. She	Ph.D.	Physics	2 mo/yr
Joe Vance	grad. student	Physics	travel only
Kam Arnold	undergrad.	Physics	travel only
Phil Acott	undergrad.	Physics	travel only

Publications Citing this AFOSR Support (current and anticipated):

She, C.-Y., J. Vance, B. Williams, H. Hu, D. Krueger, H. Moosmuller, D. Gibson-Wilde, and D. Fritts, A new sodium lidar in ALOMAR (69N, 16E) and the first 24-hour continuous temperature observation in the arctic summer mesopause region, EOS, 27, 289-293 (including cover), 2002.

Fritts, D. C., S. A. Vadas, and Y. Yamada, 2002: An estimate of strong local gravity wave body forcing based on OH airglow and meteor radar observations, Geophys. Res. Lett., 29, 10.1029/2001GL013753.

Vadas, S. L., and D. C. Fritts, 2002: The importance of spatial variability in the generation of secondary gravity waves from local body forces, Geophys. Res. Lett., 29,10.1029/2002GL015574.

Arnold, K. S., and C.-Y. She, 2002: Metal fluorescence lidar (light detection and ranging) and the middle atmosphere, Contemporary Physics, 44, 35-49.

Fritts, D. C., C. Bizon, J. A. Werne, and C. K. Meyer, 2003: Layering accompanying turbulence generation due to shear instability and gravity wave breaking, J. Geophys. Res., in press.

Fritts, D.C., and M.J. Alexander, 2003: Gravity Wave Dynamics and Effects in the Middle Atmosphere, Rev. Geophys., 41, 10.1029/2001RG000106.

Vadas, S. L., and D. C. Fritts, 2003: Thermospheric responses to gravity waves arising from mesoscale convective complexes, J. Atmos. Solar Terres. Phys., in press.

She, C.-Y., B. P. Williams, K. Arnold, and D. Krueger: Are temperatures in the arctic summer sporadic sodium layer anomalous?, in preparation.

Williams, B. P., C. Y. She, J. D. Vance, K. Arnold, P. Acott, D. A. Krueger, and D. C. Fritts: Summer polar mesopause region temperatures measured in 2001 by the ALOMAR Weber sodium lidar, in preparation.

Williams, B. P., D. Gibson-Wilde, D. C. Fritts, C.-Y. She, and J. Vance: Initial polar mesosphere dynamics observed with the Weber lidar at ALOMAR, Norway, in preparation.

Williams, B. P., J. Vance, K. Arnold, C. Y. She, D. E. Gibson-Wilde, D. C. Fritts, W. Singer, and R. Latteck, 2003: Comparison between Sodium Lidar, Medium Frequency Radar and Meteor Radar Wind Observations at ALOMAR, Norway, in preparation.

Goldberg, R. A., D. C. Fritts, F. J. Schmidlin, F.-J. Luebken, T. Blix, C. Croskey, J. Mitchell, M. Friedrich, U.-P. Hoppe, M. Rapp, and B. Williams, 2003: An overview of the MaCWAVE/MIDAS summer rocket campaign at Andoya, Norway: Instrumentation and science focus, Geophys. Res. Lett. (special section), in preparation.

Schmidt, G., W. Singer, R. Latteck, B. Williams, D. C. Fritts, 2003: Mesopause tidal structure during the MaCWAVE/MIDAS rocket campaign, Geophys. Res. Lett. (special section), in preparation.

Williams, B., J. Vance, C.-Y. She, D. C. Fritts, F. J. Schmidlin, R. A. Goldberg, U.-P. Hoppe, R. Latteck, W. Singer, M. Rapp, and F.-J. Luebken, 2003: Evidence of unusually high gravity wave variability near the summer mesopause during the summer MaCWAVE/MIDAS rocket campaign, Geophys. Res. Lett. (special section), in preparation.

Rapp, M., F.-J. Luebken, R. Latteck, W. Singer, D. C. Fritts, R. A. Goldberg, F.-J. Schmidlin, C. Croskey, and J. Mitchell, 2003: Inference of gravity wave dissipation and mean-flow interactions from in situ and ground-based data during the summer MaCWAVE/MIDAS rocket campaign at Andoya, Norway, Geophys. Res. Lett. (special section), in preparation.

Fritts, D. C., B. Williams, J. Vance, C.-Y. She, F. J. Schmidlin, R. A. Goldberg, F.-J. Luebken, and M. Rapp, 2003: Measurements and implications of extreme gradients of wind and temperature near the summer mesopause during the summer MaCWAVE/MIDAS rocket campaign, Geophys. Res. Lett. (special section), in preparation.

Fritts, D. C., and M. J. Alexander, 2003: Gravity wave dynamics and effects in the middle atmosphere, Rev. Geophys., 41, doi: 10.1029/2001RG000106.

Technical Presentations to date:

Vance, J. D., C. Y. She, B. P. Williams, Z. Hu, and D. A. Krueger, ALOMAR Weber Sodium Lidar: A new lidar for measuring temperature and dynamics in the Arctic mesopause region, AGU 2000, SPA-Aeronomy.

She, C.-Y., A New Lidar is born at ALOMAR, Presentation at the 27th Atmospheric Optical Meeting, Stockholm, August 21-25, 2000.

Williams, B. P., C.-Y. She, J. Vance, K. Arnold, D. E. Gibson-Wilde, and D. C. Fritts, First scientific results with the Weber sodium lidar at the ALOMAR observatory, CEDAR Summer Symposium, June, 2002.

Goldberg, R. A., and D. C. Fritts, An overview of MaCWAVE: A program to study gravity wave forcing of the polar mesosphere and lower thermosphere during summer and winter, IUGG Symposium, Sapporo, July 2003.

Vance, J., K. Arnold, and C.-Y. She, Technology and the ALOMAR Weber Sodium lidar, U.S. Japan Symposium on Dynamics and Airglow, Jackson Hole, September 2003.

Invention Disclosures and Patents granted:

None during this period.

Invited Lectures, Presentations, Talks, Etc.:

She, C.-Y., A New Lidar is born at ALOMAR: A story of measuring global atmospheric temperatures atmospheric temperatures between 80 and 110 km, Seminar on 10.6.00 at FFI, Norway.

Fritts, D. C., Dynamics and Effects of Gravity Wave Breaking, PSMOS Symposium, Iguacu Falls, October 2002.

She, C.-Y., 2003: CEDAR Prize Lecture: Sodium lidar studies of the mesopause region, Longmont, June 2003.

Fritts, D. C., Gravity wave forcing and imposed variability in the MLT region, IUGG Symposium, Sapporo, July 2003.

Fritts, D. C., What Can Airglow and Correlative Measurements Teach Us About Gravity Wave and Instability Dynamics?, U.S. Japan Symposium on Dynamics and Airglow, Jackson Hole, September 2003.

Fritts, D. C., On Evolution and Natural Selection in Elephants (a review of the historical developments and current controversies in gravity wave saturation theories), U.S. Japan Symposium on Dynamics and Airglow, Jackson Hole, September 2003.

Professional Activities:

Our efforts during this research involved close collaborations with our European partners at ALOMAR and additionally with German, Norwegian, and U.S. colleagues in the performance and data analysis supporting the MaCWAVE rocket campaigns. The first activities focused on enhancing and coordinating joint lidar measurement capabilities at ALOMAR and training of additional staff for operations of the Weber lidar. Participants included all of the Weber lidar team at CSU and CoRA. Participation in the MaCWAVE rocket programs and associated analysis included Fritts, She, Williams, and Vance.

Honors Received (include lifetime honors such as Fellow, honorary doctorates, etc., stating year elected):

D. Fritts was listed among the top 0.5% of cited researchers by http://www.isihighlycited.com.

C.-Y. She was honored with the CEDAR Prize Lecture at the 2003 CEDAR Summer Meeting.

Extended Scientific Visits From and To Other Laboratories:

Dr. Joe She participated during this contract period as a Fulbright Scholar with the Norwegian Defense Research Establishment and the University of Oslo in association with the Weber lidar project at ALOMAR.

All seven CoRA and CSU personnel have participated in visits of various durations for work with the Weber lidar measurement activities at the ALOMAR observatory during the performance of this research.

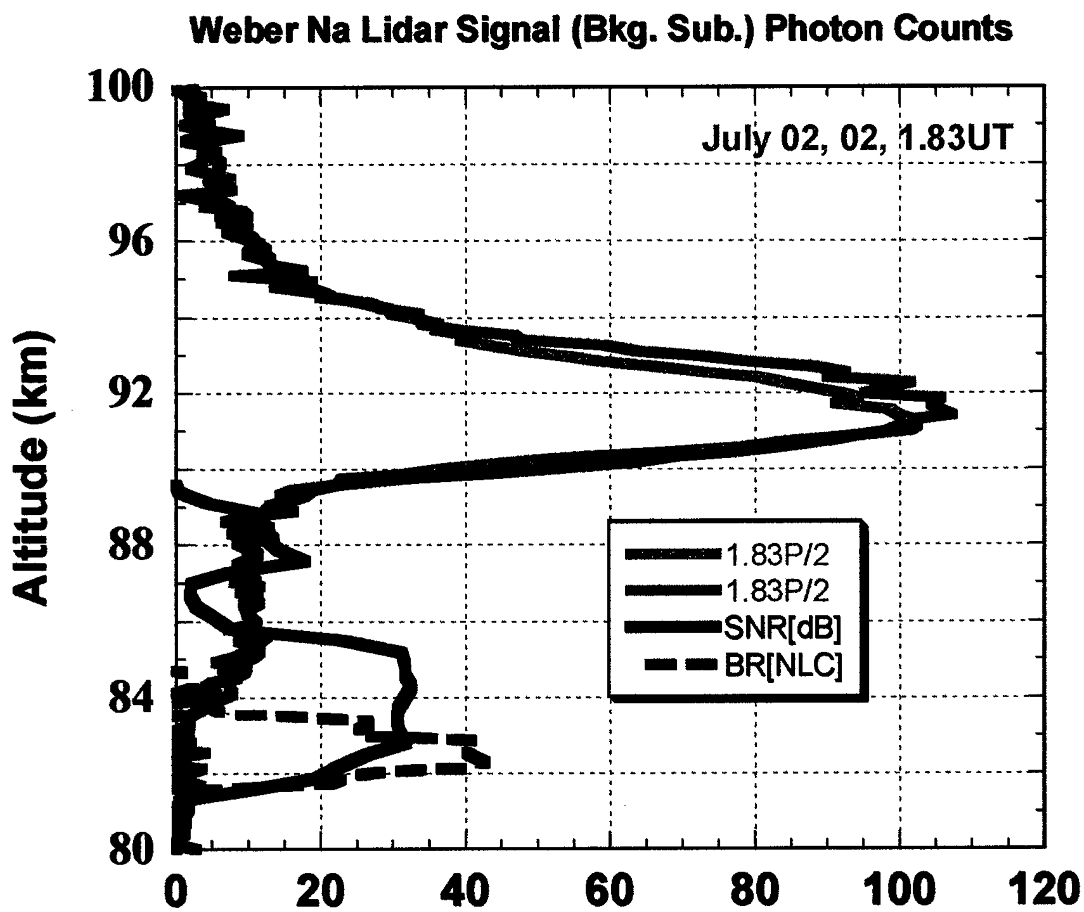

Figure 1. Photon counts from the east (blue) and west (red) beams of the Weber lidar in 75-m range bins with a 1-min integration obtained on 2 July (under sunlit conditions) during the first sequence of the MaCWAVE/MIDAS rocket campaign at the Andoya Rocket Range and the ALOMAR observatory at Andennes, Norway. Also shown with solid and dashed lines are the signal-to-noise ratio (SNR) for the ALWIN VHF radar and the backscatter ratio (BR) indicating the presence of noctilucent clouds (NLC). Note that strong NLC and atomic sodium do not co-exist, that visible NLC occur at the lower edge of radar SNR, and that large sodium densities occur only above altitudes exhibiting strong radar backscatter.

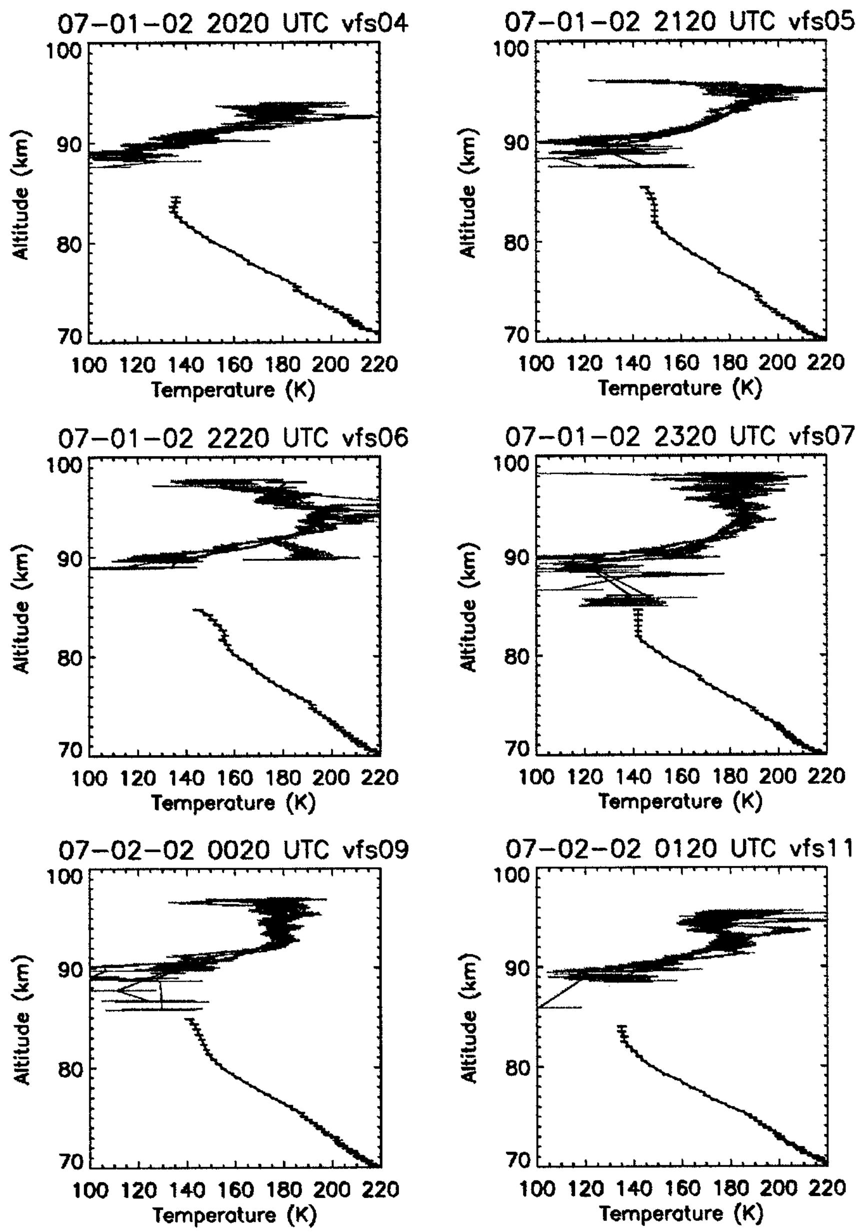

Figure 2. Hourly temperature profiles and uncertainties based on photon statistics in the east (blue) and west (red) beams of the Weber lidar for six times during the first MaCWAVE/MIDAS salvo during July 2002. Despite a thin and depleted sodium layer and full sunlit conditions, temperature estimates were possible in the presence of extreme gradients in the lower thermosphere. Data at lower altitudes are from the corresponding MET rocket falling sphere soundings and illustrate the extreme differences in altitude resolution of the two techniques near the mesopause.

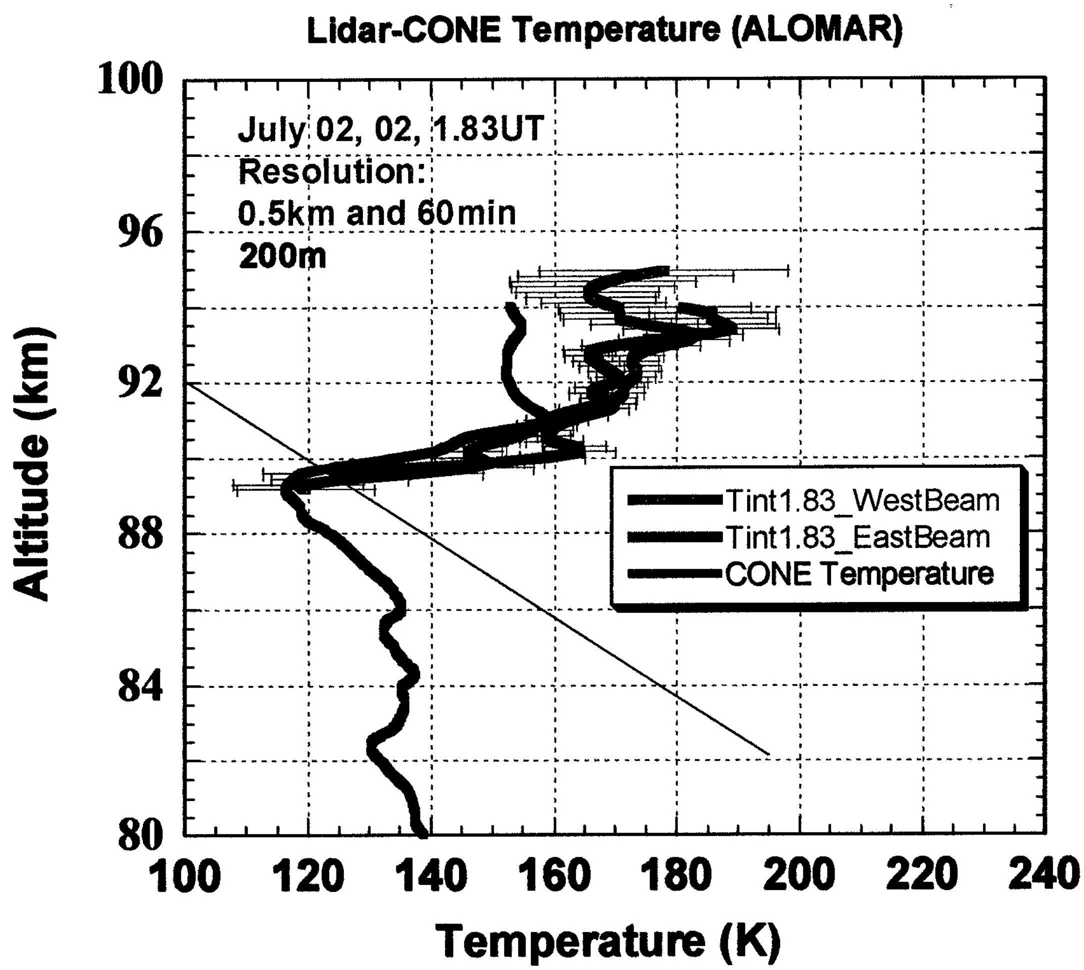

Figure 3. Temperature profiles obtained with the Weber lidar in the east (blue) and west (red) beams with 500-m and 1-hr resolution and with the CONE ionization gauge aboard the MIDAS sounding rocket during the first MaCWAVE/MIDAS summer salvo. Differences between the profiles are attributed to measurements at different locations in a very dynamically active mesopause gravity wave field. Spacing between the lidar beams (at 20° zenith angles) was ~60 km and the CONE measurement was ~30 km north of the west beam of the lidar. Steep gradients range from ~50 K/km for CONE to ~100 K/km or greater for the Weber lidar.

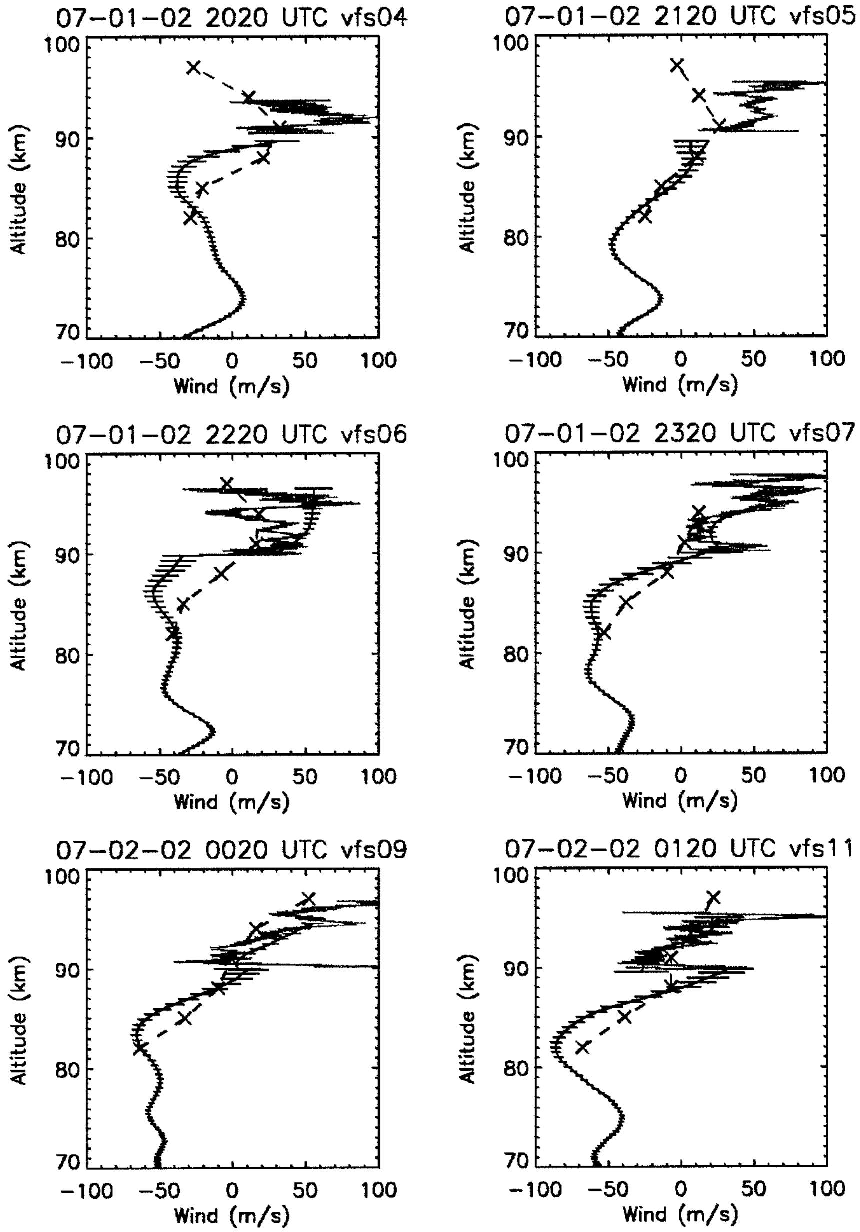

Figure 4. As in Figure 2, but for zonal winds representing an average of the east and west beams of the Weber lidar. Despite a thin and depleted sodium layer and full sunlit conditions, wind estimates were still possible and found to yield much better resolution than either the meteor radar ("x"s) or falling spheres at lower altitudes.

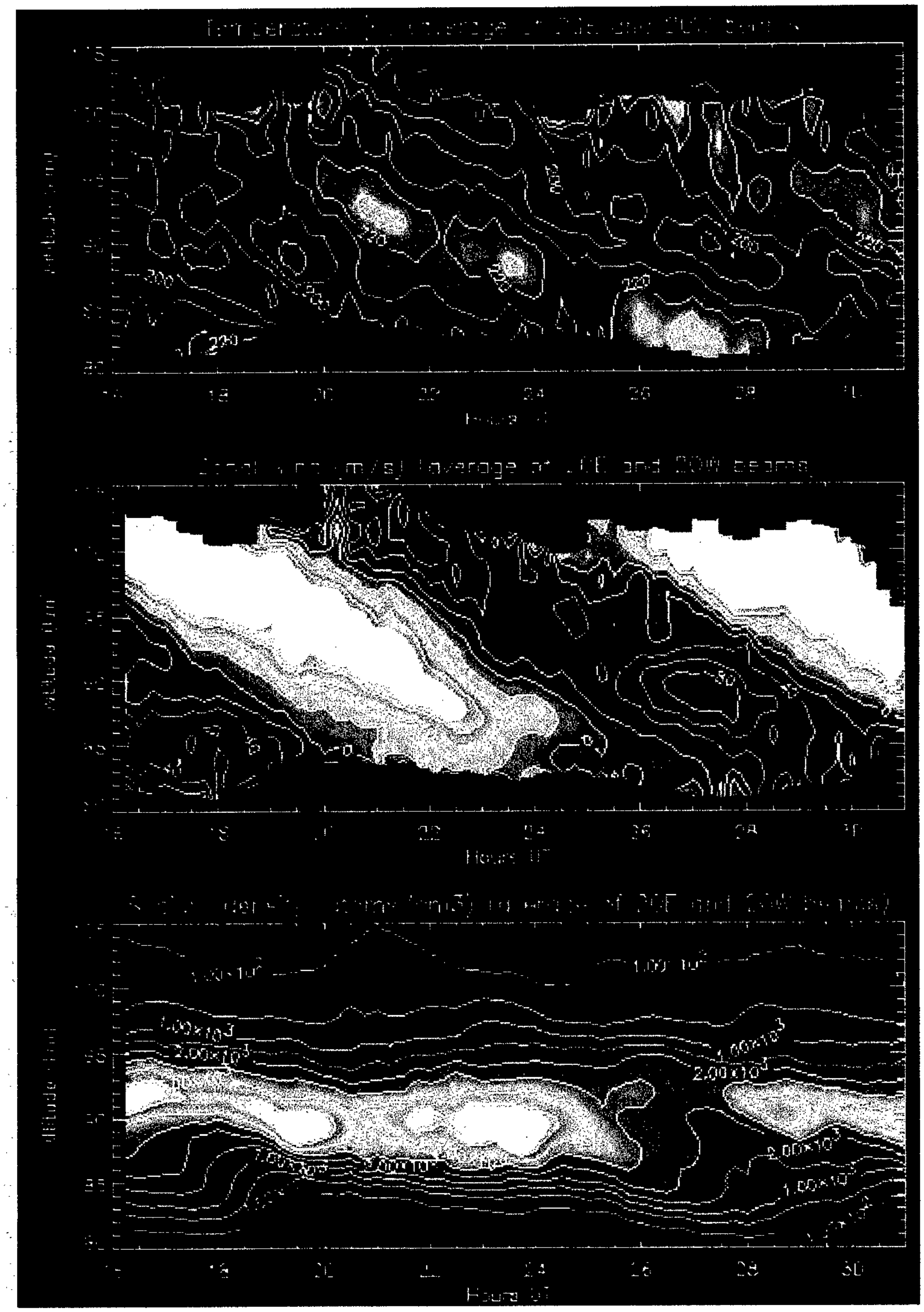

Figure 5. Temperature (top), zonal wind (middle), and sodium density (bottom) cross sections obtained during the long measurement sequence performed in support of the winter MaCWAVE rocket sequence in January 2003. The data have yet to be fully analyzed, but indicate a very large semi-diurnal tidal structure with enhancement either due to nonmigrating tidal components or superposed large-amplitude gravity waves. Peak winds are ~ 100 m/s and peak temperature perturbations are ~ 30 to 40 K. Note that the altitude extent and sodium densities are much greater than under summer conditions, yielding more extended and more accurate wind and temperature estimates.